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Pulse code modulation of video signals: subjective study of coding parameters

No. 1971/40

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

PULSE CODE MODULATION OF VIDEO SIGNALS: SUBJECTIVE STUDY OF CODING PARAMETERS

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D. Maurice

V.G. Devereux, M.A.

Head of Research Department

(EL-57)

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October 1971

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PULSE CODE MODULATION OF VIDEO SIGNALS: SUBJECTIVE STUDY OF CODING PARAMETERS

Summary

This report describes subjective tests performed to establish the sampling rate and the number of bits per sample which should be used in a p.c.m. system handling broadcast quality television pictures. These tests included an investigation of adding 'dither' signals to the video signals prior to the p.c.m. encoder as a means of reducing the required number of bits per sample. (The effect of dither signals is to break up coherent quantising errors such as 'contouring' effects and replace them with less noticeable random quantising errors.)

A theoretical estimate of the required number of bits per sample is derived by comparing calculated values of the magnitude of quantising noise with the existing specification for random noise allowable on analogue links.

1. Introduction

Recent advances in digital technology have made it possible in principle to replace much of the analogue equipment used in the processing and transmission of television signals by equivalent digital equipment. Although digital methods may not be applied extensively to television broadcasting for some years, the specification of p.c.m. links capable of handling digital video signals is already being given considerable attention by international committees. It is therefore essential that the optimum parameters of a digital system capable of handling colour television signals of broadcast quality should be determined as soon as possible.

This report describes the results of subjective tests on the effect of varying the sampling rate and the number of bits per sample in a p.c.m. system handling System I monochrome or PAL-colour 625-line video signals. These tests included an investigation of the effectiveness of dither signals as a means of reducing the number of bits required for acceptable picture quality. The function of these dither signals is discussed in Section 3.4.

Before the subjective tests were undertaken, an attempt was made to deduce the number of bits required per sample by comparing the theoretical quantising noise power produced by different numbers of bits with the random noise power allowable in analogue systems. This theoretical analysis is described in Section 3.4 and it will be seen that the results obtained were in good agreement with the results of the subjective tests given in Section 5.

The p.c.m. encoder and decoder used for the tests has been described in a previous report.[1]

The reasons for using p.c.m. rather than such systems as differential p.c.m. or delta modulation are discussed in the next section.

2. Choice of digital coding system

In selecting a coding system for television, both point-to-point transmission and signal processing operations have to be considered.

For transmission along national and international networks, a coding system which can accept the standard composite colour signal is essential, because most networks will, during their evolutionary stages, have analogue sections interspersed with the digital sections. Digital systems in which the luminance and colour difference signals are encoded separately[2] could not therefore be used for normal broadcast transmissions since the additional colour coding and decoding processes required at the ends of the digital sections would cause an unacceptable degradation of the final picture quality. Since, therefore, it is necessary to encode the composite colour signal, large amplitude high-frequency components which are often provided by the colour subcarrier have to be encoded with about the same precision as low-frequency components. This requirement is fulfilled by linearly coded p.c.m. but is not normally fulfilled by delta modulation or differential p.c.m. since any advantages of these latter systems are only obtained at the expense of loss of accuracy of high-frequency detail.

As far as signal processing is concerned, arithmetic operations such as mixing, aperture correction and standards conversion can be effected much more easily with p.c.m. signals than with those obtained from differential p.c.m. or delta modulation.

The optimum coding law to use for p.c.m. would be one giving constant visibility of the brightness changes corresponding to each change of one quantum level in the video signal.[3] This condition is very nearly satisfied by a linear coding law applied to gamma corrected video signals. Since the optimum law would involve considerable extra instrumental difficulties, a linear law is the most suitable for practical purposes. Linear coding also has the advantage that quantising errors in the colour subcarrier are independent of the luminance level.

It would therefore appear that linearly coded p.c.m. is the most useful coding system for general use in television broadcasting.

3. Factors affecting choice of parameters of p.c.m. system

3.1 Choice of sampling frequency

By Nyquist's sampling theorem, the theoretical minimum sampling frequency is twice the highest video frequency, i.e. 11 MHz for a video bandwidth of 5·5 MHz. However, it is necessary to precede and follow the digital system by 5·5 MHz low pass filters and to allow for the finite rate of cut-off of practical filters, the minimum sampling frequency which can be used in practice is about 13 MHz.[4]

Another factor to be considered is that the quantisation of a sampled signal can cause beat patterns in coloured areas of a picture by intermodulation between the sampling and the colour subcarrier frequency components. The amplitude of these beat patterns depends on the number of bits per sample and is decreased by 6 dB for each additional bit. For a given number of bits, the visibility of the patterns is minimised if the sampling frequency is an integral multiple of subcarrier frequency,[5] i.e. of 4·43 MHz for 625-line PAL signals. A suitable multiple is three since it gives a sampling frequency of 13·30 MHz, which is only just above the minimum practical sampling frequency.

System requirements can also effect the final choice of the sampling frequency. For example, digital processing operations in which the signal is required to be delayed by exact multiples of a line period are made easier if the sampling frequency is an integral multiple of line frequency. On the other hand, the need to multiplex digital video signals with other forms of data may mean that the sampling frequency may be dictated by other users of the point-to-point transmission system.

Taking into account the various factors given above, three different sampling frequencies were selected for use in subjective tests, these being:

(a) Three times subcarrier frequency i.e. 13·301 MHz.
(b) 851 times line frequency, i.e. 13·297 MHz. (The multiple 851 gives a frequency as close as possible to three times subcarrier frequency.)
(c) An unlocked frequency, within 1% of (a) and (b), which was selected to provide high visibility beat patterns.

These frequencies will be denoted by 3 fsc, 851 f_L and 'unlocked' respectively.

3.2 Effects of insufficient bits per sample

If each sample is represented by a binary number containing 'n' digits, the analogue signal obtained by decoding the digital signal is quantised into 2^n separate levels. The types of picture impairment caused by this quantisation process can conveniently be divided into three types:—

(a) Contouring effects: Areas of the picture in which the brightness varies slowly with position are represented by patches of uniform brightness separated by sharp transitions. The appearance of this effect is reminiscent of shaded contours on a map.
Contouring effects tend to be masked by fine patterns which cause the signal to cross quantum levels at closely spaced intervals; in this respect, colour subcarrier has a similar effect, and contours are therefore not in general as noticeable with colour signals as with monochrome signals.
(b) Beat patterns on colour pictures. These have been discussed in Section 3.1 and result from the intermodulation of the colour subcarrier and sampling frequency components. They are most noticeable in areas of constant hue and saturation.
(c) Increase in noise. Random noise on the video signal at the input of the digital coder tends to break up both contouring and beat patterning effects; the quantising errors then appear as additional noise on the picture.

Increasing the number of bits per sample rapidly reduces all of the above effects as each additional bit halves the quantising error.

3.3 Use of dither signals to reduce visibility of quantising errors

For a given number of bits per sample, the coherent patterning effects such as contouring and beat patterning are more visible than random errors and therefore the picture impairment produced by quantisation is reduced if the errors can be transformed from coherent to random form. One method of achieving this effect is to deliberately add a 'dither' signal to the video signal at the input of the digital coder.[6]

The purpose of a dither signal is to cause the video signal in the coder to repeatedly cross the quantum levels lying on either side of the original signal level. The process is illustrated in Fig. 1, in which 'x' is the difference between the original signal and the next, lower, quantising level and 'Q' is the increment between successive quantising levels. Ideally, matters should be so arranged that the mean level of the quantised signal is equal to that of the original

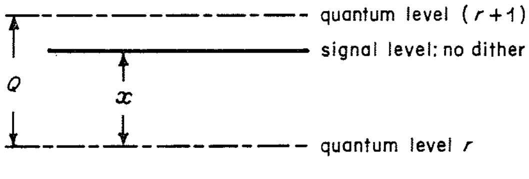

Fig. 1 - Position of signal level relative to adjacent quantum levels in coder

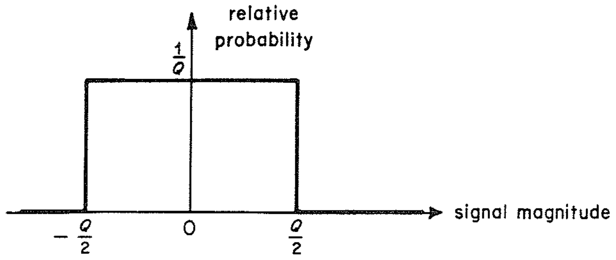

Fig. 2 - Probability distribution of ideal dither signal

signal. To this end, the dither signal should be such that the times spent by the quantised signal at the upper and lower of the two levels shown in Fig. 1 should be equal to (Q − x)/Q and x/Q respectively. This requirement is achieved if the instantaneous magnitude of the dither signals has uniform probability of lying anywhere in the range ± $Q/2$, and zero probability of lying outside this range (see Fig. 2).

Dither waveforms may be random, pseudo-random or periodic. Using Gaussian random noise as the dither signal, preliminary subjective tests showed that contouring and beat patterns are substantially eliminated if the r.m.s. amplitude of the Gaussian noise 'σ' is greater than about 0·35Q. With σ = 0·35Q, the amplitude probability distribution of the random Gaussian dither signal is as shown in Fig. 3. (Comparing Figs. 2 and 3 shows that Gaussian noise can never completely satisfy the requirements of an ideal dither signal.) The power in Gaussian noise with σ = ·35Q is 2 dB greater than the quantising noise power obtained with quantum levels separated by Q and therefore the elimination of the coherent quantising errors is obtained at the expense of a degradation in the overall signal-to-noise ratio of the digital system to 4 dB below that given by quantising noise alone.

These tests on Gaussian dither signals show that noise present in the original signal is sufficient by itself to eliminate coherent quantising errors if the original unweighted signal-to-noise ratio is lower than about (6n + 5) dB where n is the number of bits per sample. (This expression for signal-to-ratio is obtained by subtracting the 2 dB mentioned in the previous paragraph from the calculated value of signal-to-quantising noise ratio given in Appendix I.)

Using the number of bits per sample likely to be required for broadcast television (see Section 3.5), the signal-to-noise ratios of most present-day picture sources are, indeed, lower than (6n + 5) dB; the main exceptions to this rule occur during a fade or with certain types of caption. Thus while dither is necessary on some critical pictures, its only effect on the majority of broadcast programmes would be to slightly increase the random noise level. Therefore, to obtain maximum overall advantage by the use of this artifice, the degradation introduced when dither is not essential should be as small as possible.

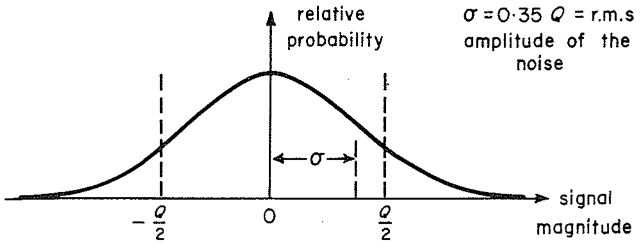

Fig. 3 - Probability distribution of Gaussian dither signal

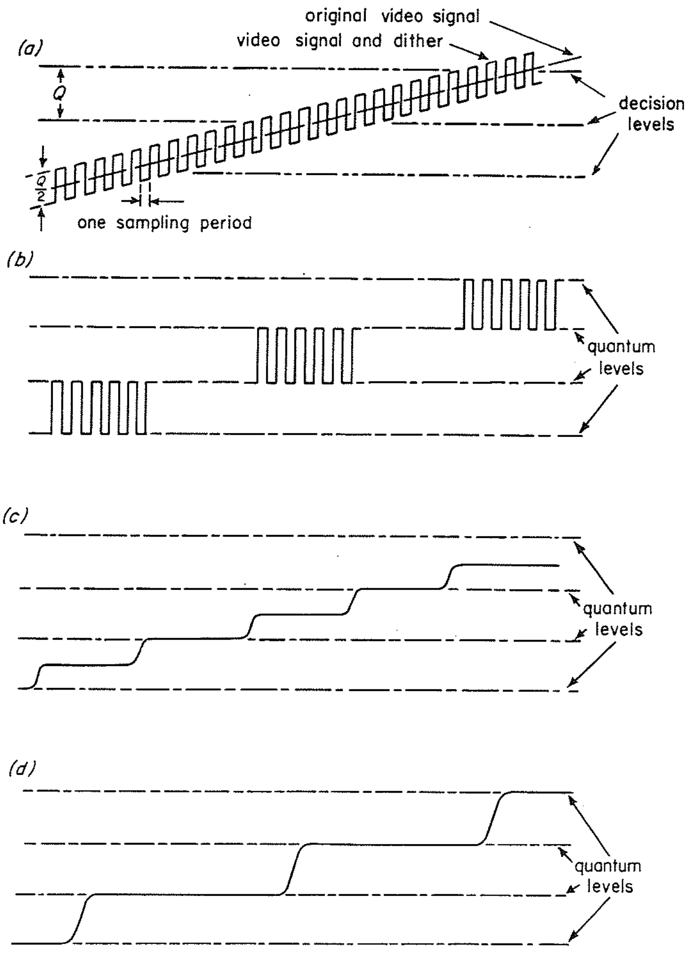

Fig. 4 - Effect of adding half sampling frequency dither to slowly changing video signal

(a) Relative positions of video signal and decision levels in coder
(b) Output of coder before filtering
(c) Output of coder after filtering using dither
(d) Output of coder after filtering if no dither were used

Improved forms of dither signal are discussed below.

A half-sampling frequency signal with an amplitude of Q/2 is an extremely useful dither signal as it has the effect of apparently doubling the number of quantum levels in plain areas of a picture while causing negligible degradation in exchange. The reason for the doubling of the apparent number of levels is illustrated in Fig. 4. From this figure it can be seen that as long as the original video signal remains within ± $Q/4$ of a decision level (see Fig. 4(*a*)), alternate samples of the resulting quantised signal lie on adjacent quantum levels (see Fig. 4(*b*)). In these circumstances the quantised signal has a mean level lying half-way between quantum levels; moreover, the frequency of alternation between quantum levels is at half sampling frequency which is above the cut-off frequency of the video low-pass filter following the decoder. As a result, in plain areas of a picture, the output of the coder after filtering (see Fig. 4(*c*)) has twice the number of levels obtained without dither (see Fig. 4(*d*)).

In principle, coherent patterns can be removed with no further degradation at all in the signal-to-noise ratio by adding a pseudo-random dither signal before coding, and subtracting an identical signal after decoding.[7,8] It has been found, however, that by using half sampling frequency plus a random noise component the additional degradation could be so small that subtraction was not worthwhile. This result is obtained by adding a dither signal consisting of a half-sampling frequency component having a peak-to-peak amplitude of $Q/2$ plus a random noise component having an r.m.s. amplitude equal to 0·18Q; the resulting probability characteristic is shown in Fig. 5. The dither noise power required is now 4 dB lower than the quantising noise power and the additional degradation in the overall signal-to-noise ratio is therefore only 1·5 dB. This type of dither signal was used for all the subjective tests on the effects of dither described in Section 4.

Since these subjective tests were carried out, it has been found that the degradation in the weighted signal-to-noise ratio caused by dither can be reduced to less than 1 dB by shaping the spectrum of the noise which is added with the half sampling frequency component; a suitable spectrum is shown in Fig. 6. This type of spectrum was obtained with both Gaussian noise and with 4-level pseudo-random noise. The combination of the pseudo-random signal and the half-sampling frequency component gave an 8-level dither signal having a probability distribution shown in Fig. 7. The discrete levels in this form of dither were not noticeable when using 6 or more bits per sample and under these circumstances, both the Gaussian and the pseudo-random noise had a similar effect on quantised pictures; the pseudo-random noise had an advantage, however in that the generating equipment was significantly easier to adjust.

As shaping the spectrum of the dither only reduced the signal-to-noise ratio by about 0·5 dB compared to the case when white Gaussian noise was used, it is not thought that this would significantly alter the results of the tests.

3.4 Estimation of number of bits per sample from specifications for the allowable noise in analogue systems

Since dither can cause quantising errors to look like random noise on an unquantised picture, it is possible to deduce the number of bits per sample required for a p.c.m. system using dither by comparing the allowable noise on analogue links with the theoretical values of the quantising noise power produced by different numbers of bits per sample. (See Appendix I.) This estimation assumes that incoherent quantising errors having a given r.m.s. value cause the same subjective impairment on a picture as random Gaussian noise having the same r.m.s. value.[8]

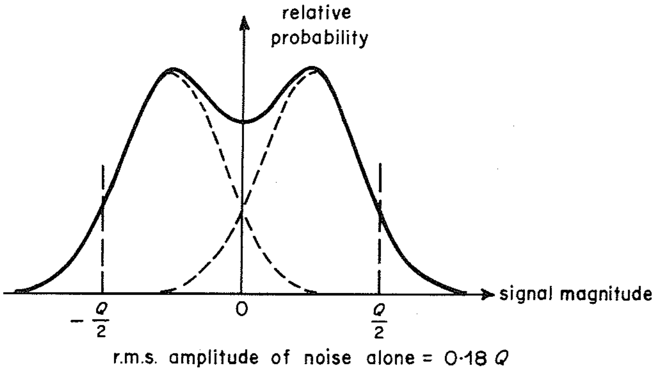

Fig. 5 - Probability distribution of Gaussian noise plus half sampling frequency dither signal

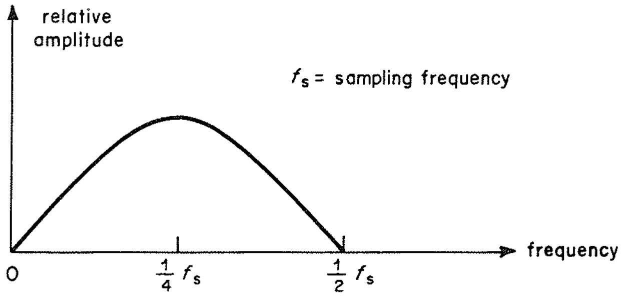

Fig. 6 - Spectrum of noise in improved form of dither signal

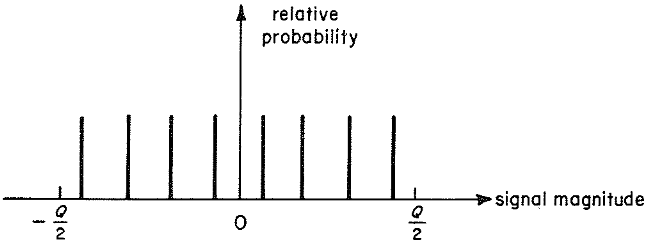

Fig. 7 - Probability distribution of 4-level psuedo-random noise plus half sampling frequency dither signal

Taking a U.K. hypothetical reference chain as representing a complete transmission system, the weighted signal/noise ratio should not be less than 52 dB for the luminance channel and 46 dB for the chrominance channel (C.C.I.R. Rec. 451-1 New Delhi 1970).

Allowing 1·0 dB degradation due to addition of dither, the weighted signal-to-noise ratios theoretically obtainable with 7, 8 and 9 bits per sample are as follows (see Appendix I):–

Bits per sample	S/N in luminance channel	S/N in chrominance channel
6	48·7 dB	47·2 dB
7	54·7 dB	53·2 dB
8	60·7 dB	59·3 dB

These figures are based on the assumption that the entire video signal including synchronising pulses and 100% saturated colours are being encoded as shown in Fig. 9.

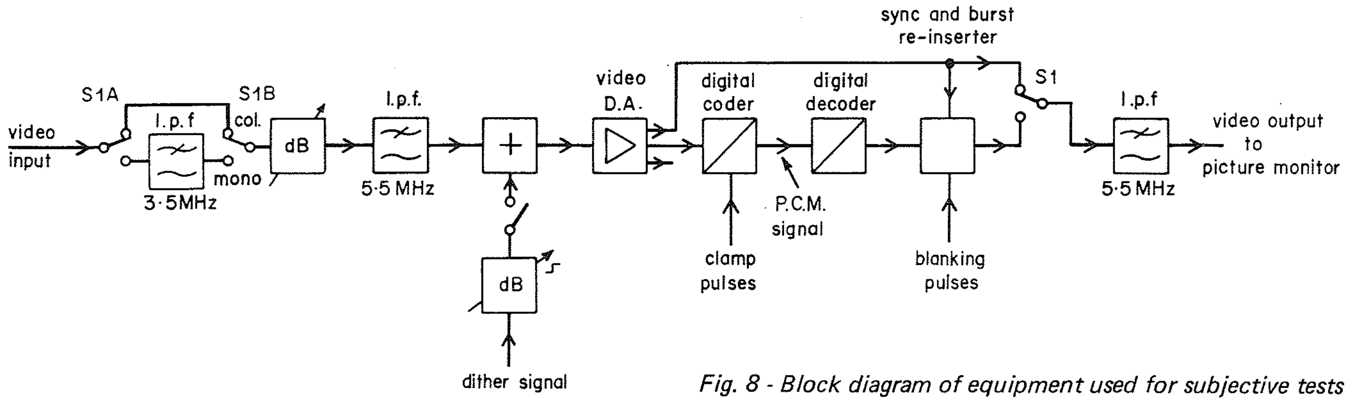

Fig. 8 - Block diagram of equipment used for subjective tests

By comparing these figures with the requirements for an analogue system, it can be seen that, in the absence of instrumental imperfections, 7 bits per sample exceeds the specified requirement by 2·7 dB in the luminance channel and 7·2 dB in the chrominance channel. Since the former requirement is the more critical, only the luminance channel is considered in the further discussions given below.

With 8 bits per sample, the quantising noise obtained from 4 codecs in tandem would again exceed the specified requirement by 2·7 dB in the luminance channel assuming that there is no correlation between the quantising errors introduced by the different codecs.

In practice, the signal-to-noise ratio may be reduced by

(a) Imperfections in the a.d.c. or d.a.c., resulting in a quantising noise greater than the theoretical value.

(b) The need to allow a factor of safety to ensure that the conversion range of the coder is not exceeded when the nominal maximum signal level is accidentally exceeded.

In the 8-bit codec already developed,[1] the signal/quantising noise ratio is about 2 dB lower than the theoretical value. It would seem reasonable to assume that coders in use by the time p.c.m. links are introduced into service will be somewhat more accurate; an allowance of 1 dB is therefore suggested for coding and decoding inaccuracies. The safety margin, remaining between the signal-to-noise ratio obtainable in practice from four 8-bit codecs in tandem and the specified requirement of 52 dB, is now 1·7 dB.

Errors in the signal level, if due to gain inaccuracy in some part of the signal chain preceding the digital system, may be avoided by the use of an automatic gain control device activated by changes in the level of a test signal in the vertical interval of the video waveform. The video signal level may not in practice bear exactly the correct relationship to the amplitude of the test signal. It will be assumed however that the margin of 1·7 dB in signal-to-noise ratio, referred to above, can be used to provide a sufficient factor of safety against excessive signal levels due to such errors; to this end, the coder would be so designed that a video signal having the correct amplitude would utilise 1·7 dB less than the full conversion range.

It should be noted that the foregoing calculations are based on the assumption that the video signal contains 100% saturated colour subcarrier which can extend 1·8 dB above white level. Since a margin of 1·7 dB has already been allowed before the conversion range is exceeded by 100% saturated colour subcarrier, it follows that white level will not exceed the conversion range until the magnitude of the video signal is 3·5 dB above normal.

If necessary a further improvement in signal-to-quantising noise ratio could be achieved by truncating the synchronising pulses at the coder beyond the lowest level reached by colour subcarrier and re-generating full amplitude pulses at the decoder. This artifice would, however, only save about 0·5 dB.

4. Subjective tests

4.1 Equipment

A block diagram of the equipment is shown in Fig. 8. The digital coder and decoder are described in Ref. 1.

The signals were displayed on a high-quality 19″ colour monitor having a peak brightness of 55 candelas/metre^2 (16 ft-L); with zero beam current, the brightness of the screen resulting from ambient illumination was 0·1 candelas/metre^2 (0·03 ft-L). Switch S2 was used to by-pass the digital equipment when the unquantised video signal was being displayed. In the coder, the video signal was clamped with the tips of synchronising pulses at the bottom of the conversion range and its amplitude adjusted so that 100% saturated subcarrier just reached the top of the conversion range (see Fig. 9).

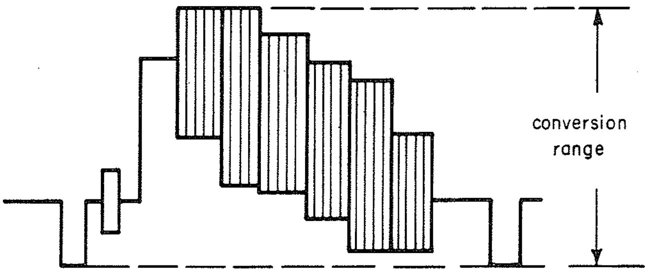

Fig. 9 - Adjustment of video levels relative to the conversion range of the coder shown for 100% colour bar signal

For the purpose of the present tests, arrangements were made to introduce unquantised synchronising pulses and colour bursts into the decoded signal thus avoiding timing or clamping errors caused by quantisation of this information. Such errors could always be substantially removed when no unquantised signal is available by relatively simple video processing techniques.

The attenuation in the dither signal path was increased by 6 dB for each additional bit per sample so that the magnitude of the dither signal remained a constant fraction of the interval between adjacent quantum levels.

4.2 Signal sources

Both moving and still pictures were used in the tests. The sources for moving pictures consisted of:–

(a) A colour camera which was panned slowly across a studio set. This set included a large plain white area, representing a fairly critical object for showing contouring effects, and also coloured curtains of various hues to provide large areas of high colour saturation.

(b) A video tape recording of a musical variety programme called 'Music, Music, Music'. The pictures were typical of good-quality, highly-coloured variety entertainment.

(c) A high-quality receiver providing live pictures of an outside broadcast of a cricket match. The signal-to-noise ratio of the receiver alone was about 40 dB unweighted.

(d) A 16 mm colour film scanner showing a film of a musical variety programme. This source was used to represent material of relatively poor picture quality on which it is difficult to see the effects of quantisation.

The sources for still pictures consisted of:–

(a) A 35 mm colour slide scanner containing a slide of which a monochrome version is shown in Fig. 10. This slide was selected as it contains relatively large plain coloured areas of low colour saturation and therefore provides a fairly critical picture for showing contouring and colour beat patterning effects.

(b) A colour bar generator adjusted to give 75% saturation. This type of signal is very critical for showing beat patterning effects. (100% colour bars were not used as they caused slightly greater instrumental errors in the digital coder but did not change the magnitude of the inherent quantising errors compared to those obtained from a 75% saturated signal.)

The inherent signal-to-noise ratios of all sources, apart from the 16 mm film scanner and the off-air receiver, were typical of the best equipment at present available.

For some of the tests, the video signal was attenuated by 8 dB prior to the digital coder in order to obtain very critical pictures.

Monochrome pictures were obtained by inserting a 3·5 MHz low-pass filter in the video path prior to the coder.

4.3 Test procedure

Each test condition was shown twice to a group of six observers seated at a distance of six times picture height from the picture monitor. The observers were all engineers or technicians having previous experience of assessing picture quality. A total of about 20 observers were used in the complete series of tests.

Picture quality was graded using the E.B.U. impairment scale given below.

Grade	Degree of Impairment
1	Imperceptible
2	Just perceptible
3	Definitely perceptible but not disturbing
4	Somewhat objectionable
5	Definitely objectionable
6	Unusable

The tests were divided into groups of 12 assessments in which the unquantised picture and quantised pictures using 4, 5, 6, 7 and 8 bits were shown twice in random order while all other test conditions remained constant. Before each group was assessed, the various types of impairment were pointed out on a 4-bit quantised picture. In addition, the unquantised picture was shown before each test picture; the type of unquantised picture shown corresponded to that used for the test picture, e.g. the unquantised picture was shown at –8 dB when the test picture was attenuated by 8 dB.

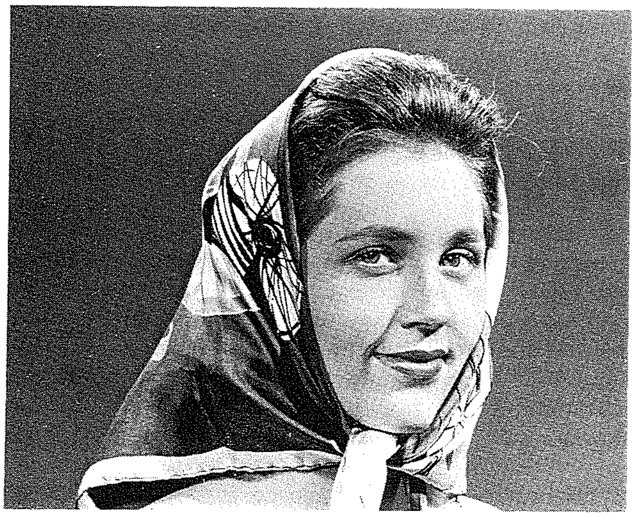

Fig. 10 - Monochrome version of slide used in tests

The possible variants in the test conditions apart from the number of bits were as follows:

- (a) Picture source.
- (b) Colour or monochrome.
- (c) Three different sampling frequencies, i.e. three times subcarrier frequency (3 f_{sc}), 851 times line frequency (851 f_L) and 'unlocked' as discussed in Section 3.1.
- (d) Dither or no dither. Dither consisted of a half sampling frequency component plus random white noise as discussed in Section 3.3.
- (e) Input signal to coder at normal level or attenuated by 8 dB.

It was not thought practicable or necessary to examine all possible combinations of these test conditions and therefore a representative selection of critical and uncritical conditions was chosen for examination.

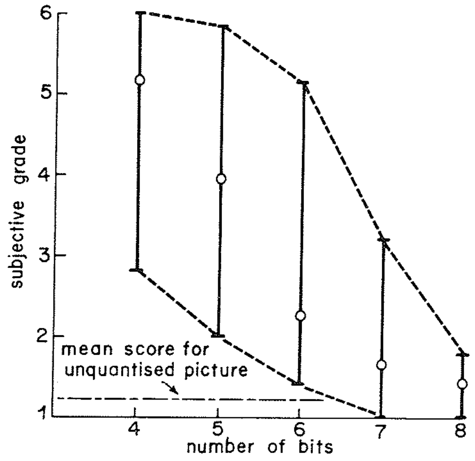

Fig. 11 - Variation in subjective impairment at different numbers of bits per sample with no dither

I Variation in grade for different picture sources
o Mean grade for all picture sources

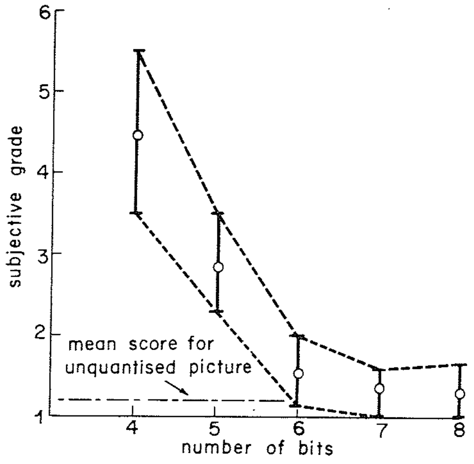

Fig. 12 - Variation in subjective impairment at different numbers of bits per sample with dither in use

I Variation in grade for different picture sources
o Mean grade for all picture sources

5. Result of subjective tests

This section gives a general analysis of the results of the tests; detailed results for all the different test conditions are given in Appendix II.

5.1 Effect of varying the number of bits per sample

Fig. 11 shows a summary of the results obtained from all the tests in which no dither was used. The upper and lower curves show the limits in grading given for different picture sources and different test conditions. (The results used for this figure were the mean score of 6 observers). It can be seen that the most critical pictures required 8 bits per sample to reduce the impairment below grade 2, while the least critical pictures required only 5 bits per sample for a grading of 2.

Fig. 12 gives the results of the tests using dither signals. From this figure, it can be seen that there is negligible advantage to be gained by using more than 7 bits per sample with dither in use.

A comparison of Figs. 11 and 12 shows that the addition of dither signals reduces the variation in the results for different test conditions and, in general, lowers the subjective impairment for a given number of bits, being most effective with the most critical types of picture.

Using 4 and 5 bits, the most critical pictures were rated slightly worse with dither than without. This was because the general noise added by dither produced greater impairment than the slight contours visible on these pictures without dither signals.

Fig. 13 shows the difference between monochrome and colour pictures with no dither. It can be seen, with small numbers of bits per sample monochrome pictures are in general degraded more than colour pictures; this is because colour subcarrier tends to act like a dither signal in breaking up contouring effects. The results plotted in Fig. 13 represent the mean scores obtained from five test conditions which were identical for both colour and monochrome pictures apart from a 3·5 MHz low-pass filter inserted in the video channel to obtain monochrome signals.

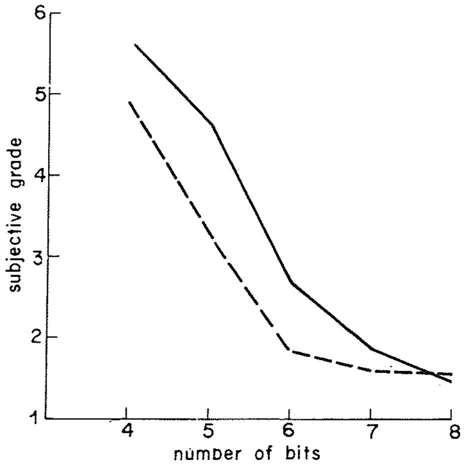

Fig. 13 - Difference in subjective impairment of colour and monochrome pictures with no dither

——— Mean grade for monochrome pictures
– – – Mean grade for colour pictures

A comparison of the results for monochrome and colour pictures showed that quantisation causes a similar degradation to both types of picture when dither is in use.

The results given above apply to the subjective impairment produced by only one codec. In deciding the number of bits required for a complete broadcasting system, some allowance has to be made for the use of several codecs in tandem. With dither in use, it is reasonable to assume that a system including 4 codecs in tandem would require 8 bits per sample to give the same picture quality as one codec using 7 bits per sample (see Section 3.4).

With no dither in use, the overall effect of several codecs in tandem will depend on the number of bits per sample and the characteristics of the video signal. Using 8 bits per sample, most picture sources will provide sufficient inherent random noise to make the quantising noise random in nature and therefore the overall effect will be the same as with dither in use. If, however, non-random quantising effects such as contouring are visible, the overall effect will depend on such factors as the relative positioning of quantising levels in the separate codecs and it is not possible to deduce any general conclusions under these circumstances.

5.2 Effect of varying the sampling frequency

With dither in use, the impairment due to beats between sampling frequency and colour subcarrier is almost imperceptible and as indicated in Figs. 14(*b*) and (*d*) there is no significant advantage in using either a locked or an unlocked sampling frequency.

With no dither, it was again found, with most types of picture, that there was little difference in the results obtained with locked or unlocked sampling frequencies. With 4 and 5 bits per sample, although there were obvious differences in the beat patterns occurring in plain coloured areas of uncritical pictures (such as those used to obtain the results given in Fig. 14(*c*)) these different effects were in general rated equally annoying. With 6 or more bits per sample it was very difficult to see the effect of changing the sampling frequency except with very critical pictures containing large uniform coloured areas such as a colour bar signal. The results for colour bars, given in Fig. 14(*a*), show that there is some advantage in sampling at exactly three times colour subcarrier frequency if less than 8 bits per sample are being used without dither. Colour bars tend to be slightly misleading, however, since each coloured strip has constant luminance, hue and saturation and therefore there is no obvious degradation due to contouring effects. These somewhat non-typical conditions account for the abnormally low grades obtained using 4 and 5 bits per sample with sampling locked to 3 times subcarrier frequency.

With all types of picture, the use of a sampling frequency locked to a multiple (851) of line frequency gave very similar results to those obtained with the unlocked frequency.

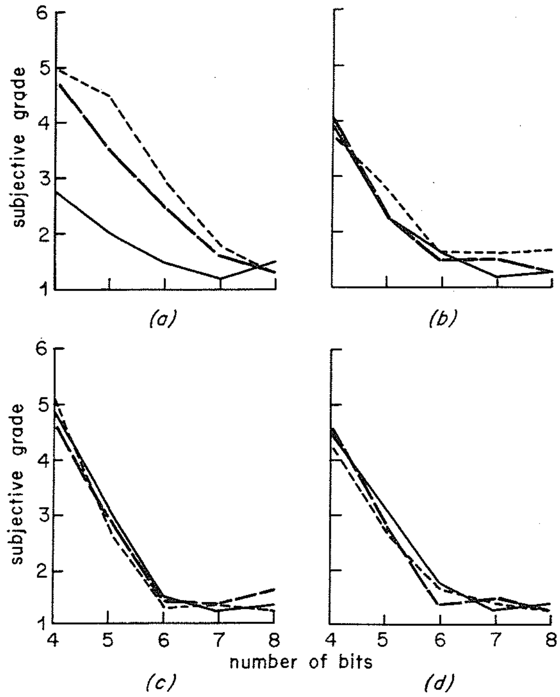

Fig. 14 - Effect of different sampling frequencies on critical picture — colour bars — and on non critical picture — picture from off-air receiver

(*a*) Colour bars; no dither (*b*) Colour bars; with dither
(*c*) Off-air pictures; no dither (*d*) Off-air pictures; with dither

——— fs = 3 x Colour subcarrier frequency
— — — fs = 851 x Line frequency - - - - fs unlocked

Sampling at 3 times colour subcarrier frequency has an advantage which is not apparent from the results of the tests. Such a sampling frequency minimises residual patterning caused by instrumental imperfections, or by overloading of the system if the video signal accidentally exceeds the conversion range of the coder thereby causing clipping of colour subcarrier components.

6. Conclusions

The tests described in this report show that, if normal subjective standards of broadcast quality are to be maintained then not less than 7 bits per sample may be used for p.c.m. encoding of television signals. 7 bits is not adequate unless

(a) dither of the optimum form described in Section 3.4. is used,

and (b) the video signal is subjected to only one coding and decoding operation.

If these conditions are not satisfied, then at least 8 bits per sample must be used. Using 8 bits per sample and dither, the video signal could be subjected to 4 coding and decoding operations.

The sampling frequency must be locked to three times colour subcarrier frequency if less than 8 bits per sample are used without dither but need not be locked with dither in use or with 8 or more bits per sample.

A comparison of the theoretical signal-to-noise ratio of a p.c.m. system using dither with the signal-to-noise ratio required on analogue links leads to the same conclusions regarding the number of bits necessary per sample.

The results obtained from the subjective tests apply when the magnitude of the video signal measured between tips of synchronising pulses and the highest level reached by 100% colour subcarrier is equal to the conversion range of the coder. With such a signal, the sync-tip to peak white amplitude is −1·8 dB with respect to the conversion range. The theoretical estimate of the number of bits per sample indicated that the results are valid when the sync tip to peak white amplitude is −3·5 dB with respect to the conversion range.

7. References

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APPENDIX I

Theoretical Video Signal-to-noise ratio introduced by a p.c.m. system

For a perfect linear quantiser with a random input signal, the ratio of the maximum peak-to-peak voltage handled by the quantiser to the r.m.s. value of the quantising noise is equal to (6·02n + 10·8) dB when n is the number of bits per sample.[10]

In order to derive the video signal-to-quantising noise ratio, several additional factors have to be considered.

Firstly, in video signal-to-noise ratio measurements, the magnitude of the signal is taken to be the voltage difference between black and white levels; in a composite colour signal, this reference voltage is 4·9 dB less than the maximum possible peak-to-peak voltage of a composite colour signal. In the present tests, the entire video signal including synchronising pulses and 100% saturated colour subcarrier was encoded, and therefore the video signal to quantising noise ratio was equal to (6·02n + 5·9) dB.

Secondly, the spectrum of the quantising noise has to be considered. The figures given above apply to the quantising noise power in the frequency range from d.c. up to one half sampling frequency i.e. up to 6·65 MHz for the sampling frequency used in the subjective tests. However, for 625-line television signals defined by System I, video signal-to-noise ratios are normally quoted for the noise power in the frequency range 10 KHz to 5 MHz.[9] Therefore assuming the quantising noise has a flat spectrum up to one half sampling frequency,[10] this bandwidth reduction increases the video signal-to-quantising noise ratio to (6·02n + 7·1) dB.

Allowing for standard noise weighting networks[9] used in System I, the weighted signal-to-quantising noise ratio becomes (6·02n + 13·6) dB for the luminance channel and (6·02n + 12·1) dB for the chrominance channel.

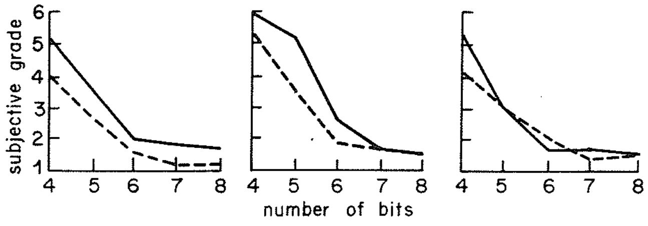
With the form of dither used in the tests, the overall signal-to-noise ratio of a digital system is 1·5 dB less than the figures given above. Using the slightly improved form of dither described in Section 3.3 the weighted signal-to-quantising noise ratios are reduced by only about 1 dB.

APPENDIX II

Detailed results of subjective tests

The results obtained for all the different conditions examined in the tests are shown in Figs. 15 to 22. A discussion of these results is given in the main part of the report.

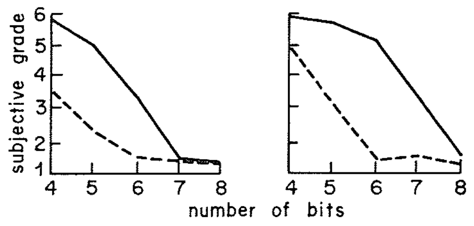
For all the figures in this appendix, the vertical axis gives the subjective impairment, using the grading scale given in Section 4.3, and the horizontal axis gives the number of bits per sample; the full lines and the broken lines represent the results obtained without and with dither respectively; fs = sampling frequency, fsc = colour subcarrier frequency and f_L = television line frequency.



(a) *(b)* *(c)*

Fig. 15 - Results for colour slide

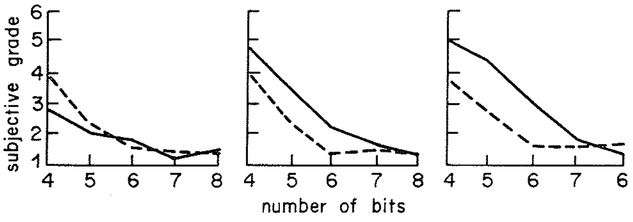
(a) fs = 851 f_L
(b) fs = 851 f_L; signal attenuated by 8 dB
(c) fs = 3 fsc
——— Results for no dither
- - - Results with dither



(a) *(b)*

Fig. 16 - Results for monochrome slide

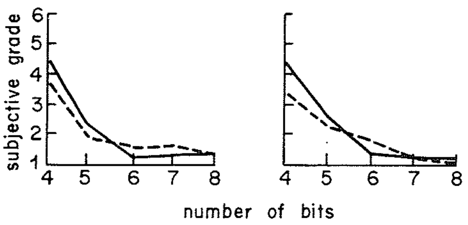
(a) fs = 851 f_L
(b) fs = 851 f_L; signal attenuated by 8 dB
——— Results for no dither
- - - Results with dither



(a) *(b)* *(c)*

Fig. 17 - Results for 75% colour bar signal

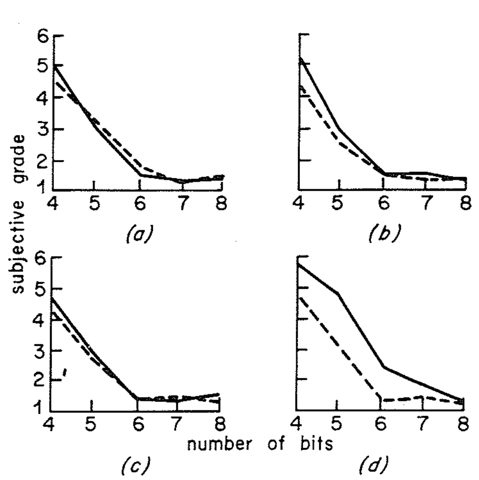
(a) fs = 3 fsc
(b) fs = 851 f_L
(c) fs unlocked
——— Results for no dither
- - - - Results with dither



(a) *(b)*

Fig. 18 - Results for video tape in colour

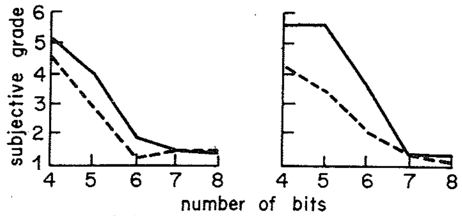
(a) fs = 3 fsc
(b) fs unlocked
——— Results for no dither
- - - Results with dither



(c) *(d)*

Fig. 19 - Results for off-air receiver pictures in colour

(a) fs = 3 fsc
(b) fs unlocked
(c) fs = 851 f_L
(d) fs = 851 f_L; signal attenuated by 8 dB
——— Results for no dither
- - - - Results with dither



(a) *(b)*

Fig. 20 - Results for off-air receiver pictures in monochrome

(a) fs = 851 f_L

(b) fs = 851 f_L; signal attenuated by 8 dB

——— Results for no dither

– – – – Results with dither

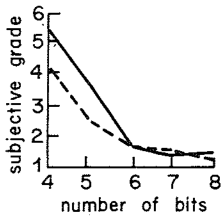


Fig. 21 - Results for colour pictures from studio camera

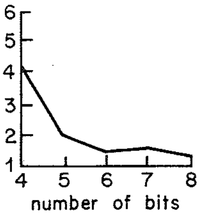


Fig. 22 - Results for 16 mm film pictures in colour

fs = 851 f_L

——— Results for no dither

– – – – Results with dither